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Development of migration models for macroinvertebrates in the Zwalm river basin (Flanders, Belgium) as tools for restoration management

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ABSTRACT

Antropogenic activities have severely deteriorated the river systems in Flanders as a result of which many functions such as drinking water supply, fishing, ... are being threatened. Because restoration of these river systems entails drastic social and economical consequences, actions should be considered in advance. In this context, migration dynamics of predicted organisms and migration barriers along the river can deliver important additional information for habitat suitability models on the effectiveness of restoration plans. To this purpose, migration models for *Baetis* (Insecta, Ephemeroptera), *Ephemera* (Insecta, Ephemeroptera) and Limnephilidae (Insecta, Trichoptera) have been developed for the Zwalm river basin, Flanders, Belgium. The migration models consisted of three resistance layers: one for migration through the air/over land and two for migration through the river in upstream and downstream direction. Based on the Cost Weighted Distance function, source populations and migration potential could be calculated. In combination with habitat suitability calculations based on Artificial Neural Networks (ANNs), the migration models were used to simulate the effect of removing a weir used for water quantity control. According to the ANN habitat suitability models, this removal did not affect the habitat suitability for *Baetis*, *Ephemera* and Limnephilidae. The ANN models predicted that after restoration the habitat was still not suitable for the taxa considered. In spite of this, the migration model for *Baetis* could be applied to simulate the possible recolonization of the restored river section in case of further habitat improvement. As calculated by the model, the shortest path with the least accumulative cost for migration would be through the air. Based on the migration model of *Baetis*, it would take approximately 275 days to recolonize the restored river.

1. Introduction

Recently, habitat suitability models such as Artificial Neural Networks (ANNs) have increasingly been used in aquatic sciences to analyse ecological patterns (e.g. Lek and Guégan, 1999; Maier and Dandy, 2000; Dedecker et al., 2004). These models are suited for dealing with ecological data, that are known to be very complex and may vary and co-vary in nonlinear fashions (Lek et al., 1996). In general, however, habitat suitability models do not include spatial and temporal relationships. Therefore, knowing the migration dynamics of the predicted organisms and migration barriers along the river might deliver important additional information on the effectiveness of restoration plans. The development of migration

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models would enable to investigate the connectivity between population patches or the possibility to migrate from a source population to recolonize a restored river section.

Recently, some studies used 'least-cost' modelling as an approach to incorporate detailed geographical information as well as behavioural aspects to measure connectivity and migration (e.g. Michels et al., 2001; Schadt et al., 2002; Adriaensen et al., 2000, 2003). This modelling tool is receiving growing attention in applied species-management projects as well as in research. Tool boxes based on the 'least-cost' algorithm are available in most current GIS packages (e.g. ArcGIS, this study; Idrisi; Michels et al., 2001) and in some specialized programs (e.g. CONNEC; Gulinck et al., 1993). The algorithm underlying this approach is similar to the method proposed by Knaapen et al. (1992). In their model, every unit (grid or raster cell) was assigned a resistance value according to its facilitating/hindering effects on the considered migration process. This value was used to calculate the connectivity between a source cell and a target cell, by adding the values of all cells crossed.

The aim of this work was to develop migration models for the mayflies *Baetis* and *Ephemera* (Insecta, Ephemeroptera) and the caddisfly Limnephilidae (Insecta, Trichoptera) in the Zwalm river basin (Flanders, Belgium). The Cost Weighted Distance function was used for this purpose. The three mentioned taxa were chosen as model organisms because they are recognized as important bio-indicators of a good water quality in river assessment systems (De Pauw and Vannevel, 1991). In addition, these taxa provide representative general insights in the migration behaviour of aquatic macroinvertebrate communities. The practical goal of the present study was to use the migration models to assess the accessibility in a restored river section, while ANN models would provide insight in the suitability of the local habitats. Both types of models were used to simulate the effects of a river restoration scenario in the Zwalm basin.

2. Material and methods

2.1. Study area and collected data

The Zwalm river basin is situated in the south of Flanders, Belgium, and is part of the hydrographical basin of the Upper-Scheldt. The Zwalm river basin drains an area of about 11,650 ha. The Zwalm river itself has a total length of 22 km (Fig. 1). To develop the migration model, an intensive monitoring campaign was set up. Therefore, a part of the Zwalm river basin of about 12 km was selected. This part contained river sites characterized by structural and morphological disturbances (weirs for water quantity control, artificial embankments, watering places for the cattle, culverted river sections, . . .), while others nearly met natural reference conditions (forests with good meandering, hollow river banks, deep/shallow variation, . . .). The selected part of the river basin was located in a region with different types of land use (urban, agricultural and industrial regions). For this study, the brooks Verrebeek, Dorenbosbeek and the upstream part of the Zwalm river were selected (Fig. 1).

The monitoring campaign consisted of two phases. The first phase consisted of an inventory of the structural and morphological characteristics along the selected part of the Zwalm river basin. The selected river parts were split up in stretches of 50 m, each marked with an upstream and downstream (X,Y) co-ordinate. In each river stretch of 50 m, the dominant type of land use (wooded area, housings, industrial sites, arable or grazing land, . . .) was monitored as well as the occurrence of domestic, industrial or agricultural discharges

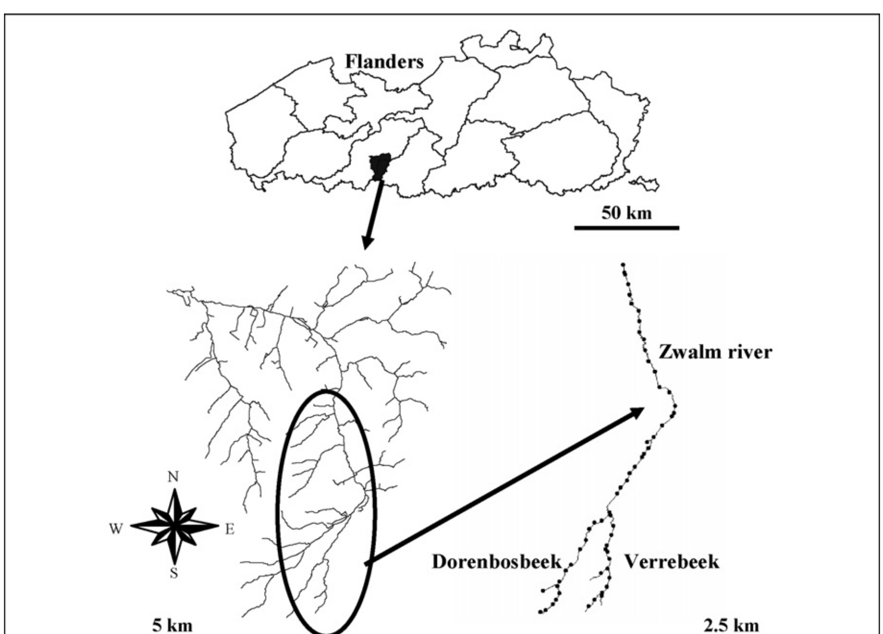


Fig. 1 – Location of the Zwalm river basin in Flanders, Belgium and the selected sampling sites in the brooks Verrebeek, the Dorenbosbeek and the upstream part of the Zwalm river.

Table 1 – Units, mean and variation of stream variables and characteristics recorded

Variables	Units	Mean	Variation
Water temperature	°C	15.0	2.4
pH		7.6	0.2
Conductivity	$\mu S\,cm^{-1}$	701.7	187.0
Suspended solids	$mg\,l^{-1}$	49.6	113.5
Dissolved oxygen	$mg\,l^{-1}$	6.6	2.0
Nitrate	$mg\,NO_3^{-}–N\,l^{-1}$	5.2	3.0
Phosphate	$mg\,PO_4^{3-}–P\,l^{-1}$	0.3	0.5
Ammonium	$mg\,NH_4^{+}–N\,l^{-1}$	0.8	1.0
COD	$mg\,l^{-1}$ COD	19.4	12.1
Total phosphorus	$mg\,P\,l^{-1}$	0.4	0.4
Total nitrogen	$mg\,N\,l^{-1}$	10.3	6.7
Water level	cm	30.0	31.2
Fraction of boulders	% of river bed (>2 cm)	33.9	37.5
Fraction of pebbles	% of river bed (2 mm–2 cm)	13.0	17.8
Fraction of sand	% of river bed (50 μm–2 mm)	23.1	23.0
Fraction of loam and clay	% of river bed (<50 μm)	27.0	26.7
Width	cm	218.7	212.4
Flow velocity	$m\,s^{-1}$	0.3	0.3
Meandering	6 classes (1: well developed to 6: absent)	4.0	1.4
Hollow river banks	6 classes (1: well developed to 6: absent)	4.3	1.4
Pools and riffles	6 classes (1: well developed to 6: absent)	4.0	1.2
Artificial embankment structures	3 classes (0: absent; 1: moderate; 2: intensive)	0.3	0.6
Distance to mouth	m	11441.1	5442.6
Stream order	4 classes (1–4)	2.4	1.2

and the presence of buffer strips along the river, natural or artificial river banks and meanders, hollow river banks and deep/shallow variation. The second phase consisted of sampling 60 sites selected in the brooks Verrebeek, Dorenbosbeek and the upstream part of the Zwalm river (Fig. 1). Each site represented a river section of about 250 m. At each site, 24 environmental variables were recorded (Table 1). Besides the macroinvertebrates *Baetis*, *Ephemera* and Limnephilidae as well as other taxa were collected by means of a standard handnet, with a mesh size of 350 μm, within a river stretch of 10 m (De Pauw and Vanhooren, 1983; IBN, 1984) and by in situ exposure of artificial substrates (De Pauw et al., 1994).

2.2. *Artificial Neural Networks*

As habitat suitability model, a multi-layer feed-forward neural network was trained using an error backpropagation training algorithm (Rumelhart et al., 1986). The structure of the applied Artificial Neural Network is presented in Fig. 2. The network consisted of 24 input variables, 10 hidden nodes and

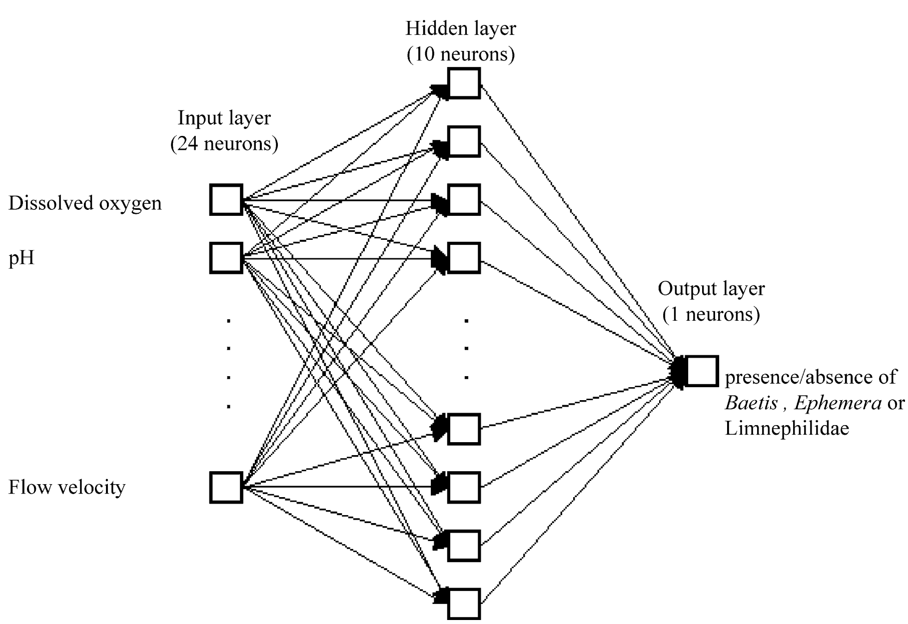


Fig. 2 – Structure of the Artificial Neural Network used in this study. The input layer consisted of the 24 input variables, the hidden layer comprised 10 neurons and the output of the network was the presence/absence of *Baetis*, *Ephemera* or Limnephilidae.

Table 2 – The confusion matrix as a basis for the performance measures with true positive values (TP), false positives (FP), false negatives (FN) and true negative values (TN)

Predicted	Observed	
	+	–
+	TP	FP
–	FN	TN

1 output variable (presence/absence of *Baetis*, *Ephemera* or Limnephilidae represented by, respectively, 1 and 0). The transfer functions were of the logistic sigmoid type. The models were evaluated on the basis of two performance measures: the percentage of Correctly Classified Instances (CCI) and the Cohen's kappa (κ). For this, one requires the derivation of matrices of confusion that identify true positive (TP), false positive (FP), false negative (FN) and true negative (TN) cases predicted by each model (Fielding and Bell, 1997). In that way, observed (actual) presence/absence patterns were tabulated against those predicted (Table 2).

The first performance measure was the percentage of Correctly Classified Instances:

$$\mathrm{CCI} = \frac{\mathrm{TP}+\mathrm{TN}}{\mathrm{TP}+\mathrm{FP}+\mathrm{FN}+\mathrm{TN}} \times 100$$

The second performance measure calculated was the Cohen's kappa (Cohen, 1960). It simply is a derived statistic that measures the proportion of all possible cases of presence or absence that are predicted correctly by a model after accounting for chance predictions:

$$\kappa = \frac{(\mathrm{TP}+\mathrm{TN}) - (((\mathrm{TP}+\mathrm{FN})(\mathrm{TP}+\mathrm{FP}) + (\mathrm{FP}+\mathrm{TN})(\mathrm{FN}+\mathrm{TN}))/n)}{n - (((\mathrm{TP}+\mathrm{FN})(\mathrm{TP}+\mathrm{FP}) + (\mathrm{FP}+\mathrm{TN})(\mathrm{FN}+\mathrm{TN}))/n)}$$

Three-fold cross-validation was used to evaluate the model performance. The training dataset consisted of 154 instances, while the test set comprised 77 instances. The removal of the weir altered the stream characteristics of 7 sampling sites. In this way, the validation dataset consisted of 7 instances. The amount of instances in which *Baetis*, *Ephemera* and Limnephilidae were present was similar in all training and test sets. The data were randomly shuffled in the training datasets to avoid biased training of the neural network. Network training was stopped when the error in the test set started to increase to avoid over-fitting. The neural network models were implemented with the software package MATLAB 6.1 for MS Windows$^{\mathrm{TM}}$.

2.3. *Data processing and migration model development*

Geographically referred data for implementation of the watercourses in a GIS were obtained from the Flemish Land Agency (VLM) who has digitalized the watercourses as linear elements in the Flemish Hydrological Atlas (MVG et al., 2000). Landscape information on the Zwalm river basin was also available in GIS vector format (polygons for the land use) from the VLM (Fig. 3). However, two problems occurred. Firstly, the brooks Verrebeek and Dorenbosbeek have not been digitalized near the sources. Also a number of tributaries of these watercourses were not digitally available in the Flemish Hydrological Atlas. Based on the (X,Y) co-ordinates of the 50 m river stretches measured on-site, these files were completed (Fig. 3). Secondly, the digitalization of the watercourses in the Flemish Hydrological Atlas has been based on 'segments'. The starting and end points of these segments have been defined as the source or the mouth of a watercourse, the confluence of watercourses or where they split off, places where the quality objectives of the surface water change, ... Because these segments were not small enough, it was impossible to link the data obtained from the inventory of the 50 m stretches, to the digital files. To solve this problem, the segments in the Flemish Hydrological Atlas were divided in stretches of 50 m (Fig. 3). Based on the inventory of the visual characteristics during the first phase of the monitoring, the biological communities and the physical–chemical variables could be extrapolated between the sampling sites, because these were supposed to be representative of the stretches upstream and downstream. In this way, the values could be set at the same level.

The migration models were developed applying ArcGIS 8.3, a product of the Environmental Systems Research Institute (ESRI) (see ESRI, 2001). One of the available extensions is ArcGIS Spatial Analyst. The Cost Weighted Distance tool of this extension was used to develop the migration models. This function finds the least accumulative cost for migrating from each cell of the resistance layer to the nearest, cheapest source. The explaining method of the Cost Weighted Distance tool is the least-cost algorithm. To move from cell N_i to cell N_{i+1}, the cumulative resistance is calculated as the resistance to reach cell N_i plus the average resistance to move through cell N_i and N_{i+1}. The function is based on an eight-neighbour-cell algorithm. As a result, also diagonal movements are allowed. In case of diagonal directions, the cost is multiplied by $\sqrt{2}$ to compensate for the longer distance (Fig. 4).

Before the Cost Weighted Distance function could be used, the vector files had to be converted into raster files (Fig. 3). The optimum size chosen for one raster or grid cell was 5 pixels. To use the Cost Weighted Distance function, two GIS layers were needed: a source and a cost or resistance layer. The source layer indicates the source populations of the modelled organisms. The resistance layer indicates both the resistance value and the geographical position and orientation of all relevant landscape components. The resistance value of each cell was based on the determining parameters affecting the migration of the organism (e.g. land use of the surrounding environment, flow velocity, migration barriers such as weirs, culverted river sections, ...). If several criteria in different measurement systems are concerned, they must be reclassified to a common scale since they cannot be compared relative to one another. In addition, the resistances were divided in a number of discrete classes. In this way, each cell of the resistance layer got a value representing the resistance for the organism to migrate through that cell.

The produced Cost Weighted Distance raster presents the least accumulated cost of getting from each cell to the nearest source population, but it does not provide the way to get there. The direction raster however gives a map, identifying the route to take from any cell, along the least-cost path, back to the nearest source population. The algorithm for computing the direction raster assigns a code to each cell that identifies which

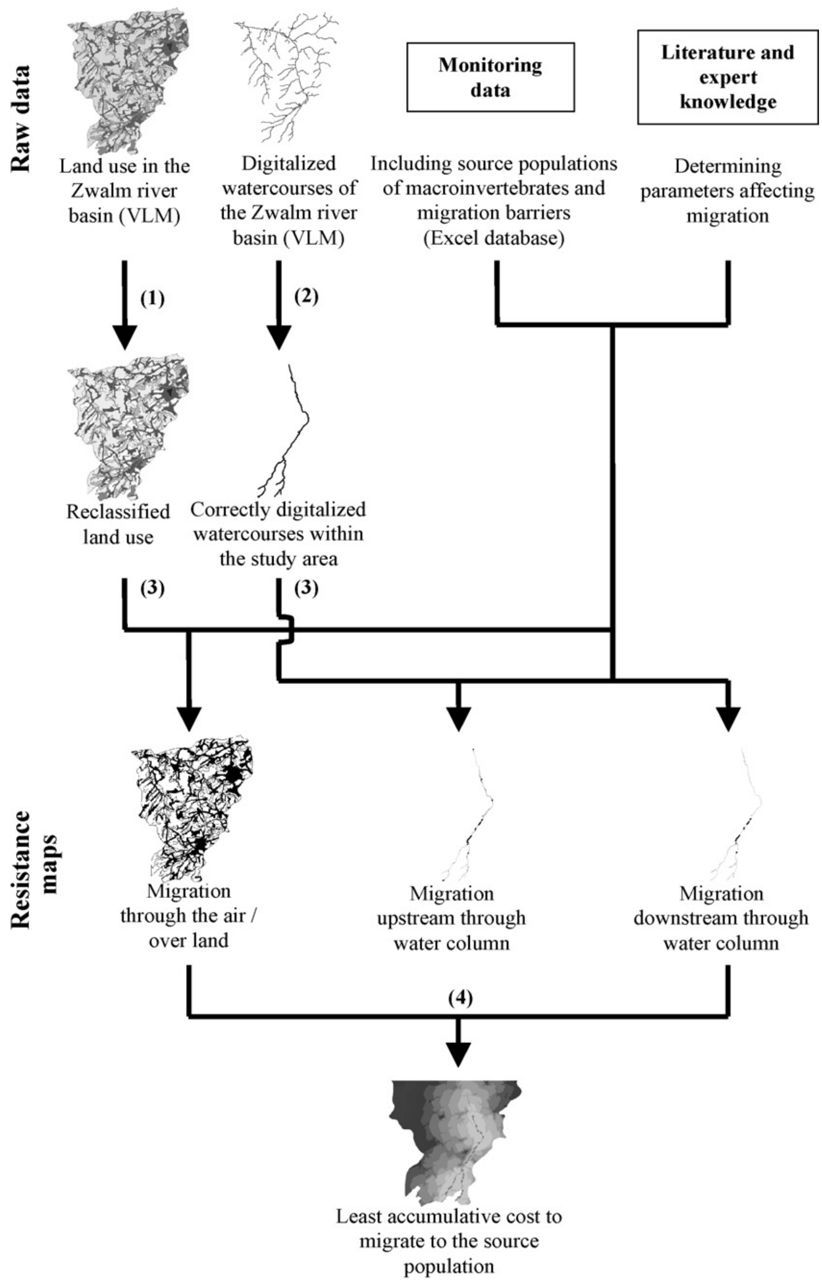
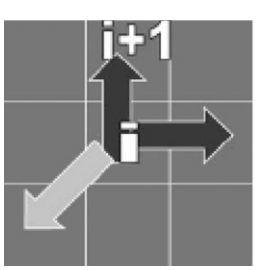


Fig. 3 – Development of a migration model for macroinvertebrates in the Zwalm river basin: (1) reclassify the land use; (2) divide 'segments' in 50 m stretches and complete digitalized watercourse file; (3) convert vector to raster file; (4) perform the Cost Weighted Distance function applying the extension ArGIS Spatial Analyst for ArcGIS 8.3.



$$N_{i+1} = N_i + (R_i + R_{i+1})/2$$
$$N_{i+1} = N_i + \sqrt{2}(R_i + R_{i+1})/2$$

Fig. 4 – The algorithm underlying the Cost Weighted Distance function. *i*: source cell; *i* + 1: target cell; N_i: accumulated resistance to reach cell *i*; R_i: the resistance to migrate through cell *i*.

one of its neighbouring cells is on the least-cost path back to the nearest source. Based on the information provided by the direction raster, a second tool, the shortest path, can be applied to compute and visualize the least-cost route from a chosen destination to the source population. In this study, both tools were combined to visualize the possibilities of the organisms to disperse from the different source populations.

2.4. *Setting of resistance values*

Three resistance layers were used: one for migration through the air/over land and two for migration through the river

Table 3 – Setting of the resistance values for migration through the air/over land ($R_{air/land}$) for *Baetis*, *Ephemera* and Limnephilidae based on the surrounding environment

Surrounding environment	$R_{air/land}$		
	Baetis	*Ephemera*	Limnephilidae
• Water surface	1	1	1
• Buffer strip (if present)	1	1	1–10
• Land use			
- Urban region	20	20	20–200
- Industrial area	20	20	20–200
- Wooded area	2	2	2–20
- Meadows	2	2	2–20
- Arable land	2	2	2–20
- Nature reserve	2	2	2–20
• Culverted river section	10–20	10–20	10–20
• Weir	2	2	2

(upstream and downstream). The setting of the resistance values (integer values) for migration through the air/over land ($R_{air/land}$) was based on expert and literature knowledge. The same resistance set was used for *Baetis* and *Ephemera*. For both macroinvertebrates, resistance values for different land use classes were chosen in such a way that resistance for movement through wooded area, meadow area, arable land or nature reserve ($R_{air/land} = 2$) was higher than for water courses and buffer strips (if present) ($R_{air/land} = 1$), but clearly lower than for hindering landscape covers such as urban or industrial areas ($R_{air/land} = 20$). $R_{air/land}$ for culverted river sections and weirs was set, respectively, at 10–20 and 2. The resistance values for Limnephilidae were based on the same values. However, studies have shown that 90% of the adult organisms of Limnephilidae were caught within a distance of 20 m from the river (Petersen et al., 1999; Winchester et al., 2002). Based on this information, a strip of 20 m around the river was taken into account. Outside this strip, the resistance value was set 10 times higher. An overview of $R_{air/land}$ for *Baetis*, *Ephemera* and Limnephilidae is given in Table 3.

The setting of the resistance values for migration upstream (R_{up}) and downstream (R_{down}) through the river was also based on expert and literature knowledge. Elliott (2003) has shown that the active migration of *Baetis* is maximum 5.5–6.0 m in the upstream and only 1.5 m in the downstream direction. The inverse value of this distance was taken as measure for the resistance to migrate actively through the river ($R_{up(active)}$, $R_{down(active)}$). Based on this and taking into account the factors affecting the active migration (e.g. presence of boulders), a resistance value was attributed to each 50 m stretch for the upstream and downstream migration. The calculation of the passive downstream migration (=drift) resistance ($R_{down(passive)}$) was based on the flow velocity and the fact that the drift distance is divided by two if macrophytes are present (Elliott, 2002):

$$\bar{x} = 8.97 \times V + 0.11$$

where $\bar{x}$ = average drift distance downstream (m) and V = flow velocity (m s^{-1}). A resistance value between 1 and 50 was obtained after rescaling and classification of the average drift distance $\bar{x}$ (Table 4). Because *Ephemera* lives in a U-shaped tunnel (in aquatic larval stadium) in the sediment, no resistance layer for migration through the river was developed for this species. In this way, they stay at the same place when no stress is observed. Based on this, *Ephemera* enters only accidentally the water mass. Therefore, it was assumed that migration through the river was only of minor importance to colonize new habitats. For Limnephilidae, resistances for migration through the river were based on the available expert and literature knowledge. Elliott (2002) showed that Limnephilidae were seldomly found in the drifting water. In this way, it can be assumed that the passive downstream migration is of less importance than the active migration. Therefore, the resistance layer for downstream migration was only based on active movements. Erman (1986) and Elliott (2003) found that the active migration of Limnephilidae species is maximally

Table 4 – Setting of the resistance values for upstream (R_{up}) and downstream (R_{down}) migration through the river for *Baetis*, *Ephemera* and Limnephilidae (n.a.: not applicable, n.s.: not significant)

	Baetis			*Ephemera*			Limnephilidae		
	$R_{up(active)}$	$R_{down(active)}$	$R_{down(passive)}$	$R_{up(active)}$	$R_{down(active)}$	$R_{down(passive)}$	$R_{up(active)}$	$R_{down(active)}$	$R_{down(passive)}$
• Boulders									
- Present	2	7	n.a.	n.s.	n.s.	n.s.	n.a.	n.a.	n.s.
- Absent	4	13	n.a.	n.s.	n.s.	n.s.	n.a.	n.a.	n.s.
• Flow velocity	n.a.	n.a.	1–50	n.s.	n.s.	n.s.	n.a.	n.a.	n.s.
• Macrophytes									
- Present	n.a.	n.a.	1–50	n.s.	n.s.	n.s.	3–6	3–6	n.s.
- Absent	n.a.	n.a.	1–50	n.s.	n.s.	n.s.	6–11	6–11	n.s.
• Natural banks									
- Present	n.a.	n.a.	n.a.	n.s.	n.s.	n.s.	3–6	3–6	n.s.
- Absent	n.a.	n.a.	n.a.	n.s.	n.s.	n.s.	6–11	6–11	n.s.
• Culverted river section	50	50	30	n.s.	n.s.	n.s.	50	50	n.s.
• Weir	200	100	100	n.s.	n.s.	n.s.	200	100	n.s.

Table 5 – Number of sampling sites and source populations of *Baetis*, *Ephemera* and Limnephilidae for each river

River	No. of sampling sites	No. of source populations		
		Baetis	*Ephemera*	Limnephilidae
Zwalm river	29	14	0	0
Brook Verrebeek	15	9	10	9
Brook Dorenbosbeek	16	7	7	4

3.5 m during 24 h in the upstream as well as the downstream direction. The inverse value of this distance was taken as measure for the resistance to migrate actively through the river ($R_{up(active)}$, $R_{down(active)}$). Based on this and taking into account the factors affecting the active migration (presence or absence of river embankments and macrophytes), a resistance value was attributed to each 50 m stretch. After rescaling and classification, a resistance value between 3 and 11 was obtained for the active upstream and downstream migration (Table 4). For *Baetis* and Limnephilidae the resistance values $R_{up(active)}$ and $R_{down(active)}$ for the weirs were set, respectively, at 200 and 100, while for the culverted river sections the resistance values were set at 50 (Table 4).

3. Results

3.1. Source populations

Sites were considered as source populations if at least two specimens of the modelled organism were found in the samples and if the river habitat quality (water and physical habitat quality) could be judged as suitable. *Baetis* was observed in the brooks Verrebeek and Dorenbosbeek and in the upstream part of the Zwalm river (Table 5). On the other hand, *Ephemera* and Limnephilidae were only found in the brooks Verrebeek and Dorenbosbeek (Table 5). In the brook Verrebeek, the latter organisms were dispersed along the whole river, while in the brook Dorenbosbeek source populations were located not further than 1.5 km downstream of that river source.

Based on the source layers including, respectively, the source populations of *Baetis*, *Ephemera* and Limnephilidae and the three resistance layers, the Cost Weighted Distance function could be used as a basis to set up migration models for the three studied taxa.

3.2. Migration model for Baetis (Ephemeroptera)

The maximum accumulative cost for migration through the air was more than 20,000 units. However, this point was of minor importance in this study. When only migration from a source population to a point in the river was taken into account, the accumulative cost was limited. The highest accumulative cost (2420 units) was reached in the most down-

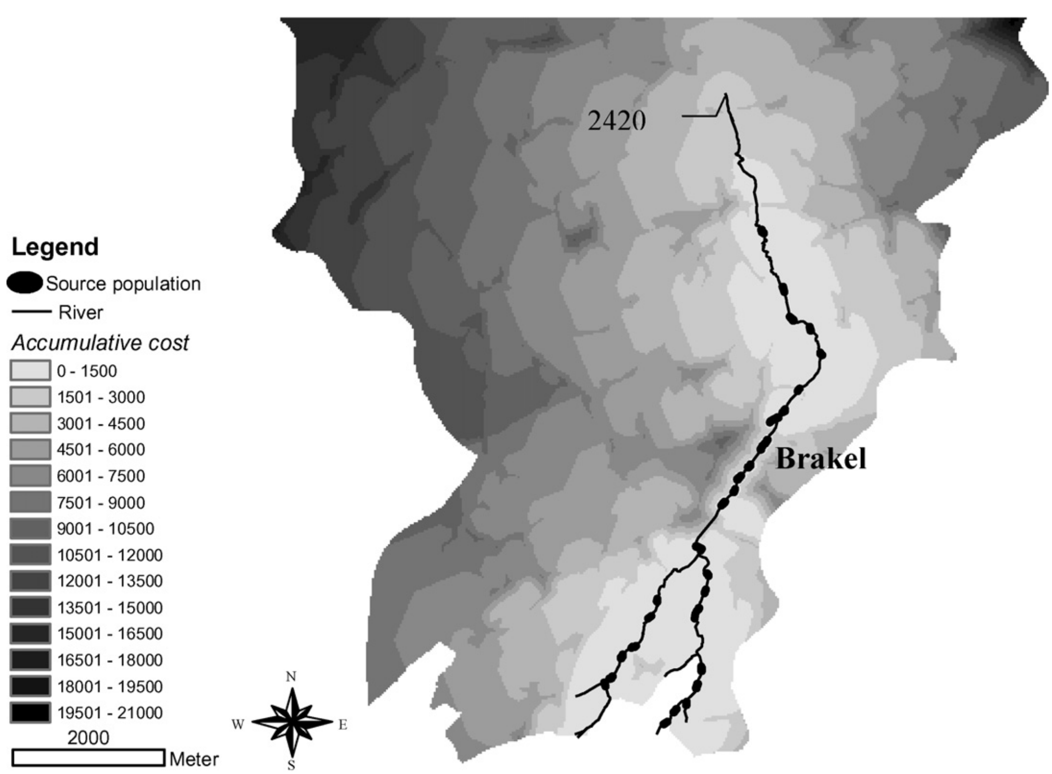


Fig. 5 – Map of the accumulative cost for migration through the air from the source populations of *Baetis*. The highest accumulative cost along the river is indicated.

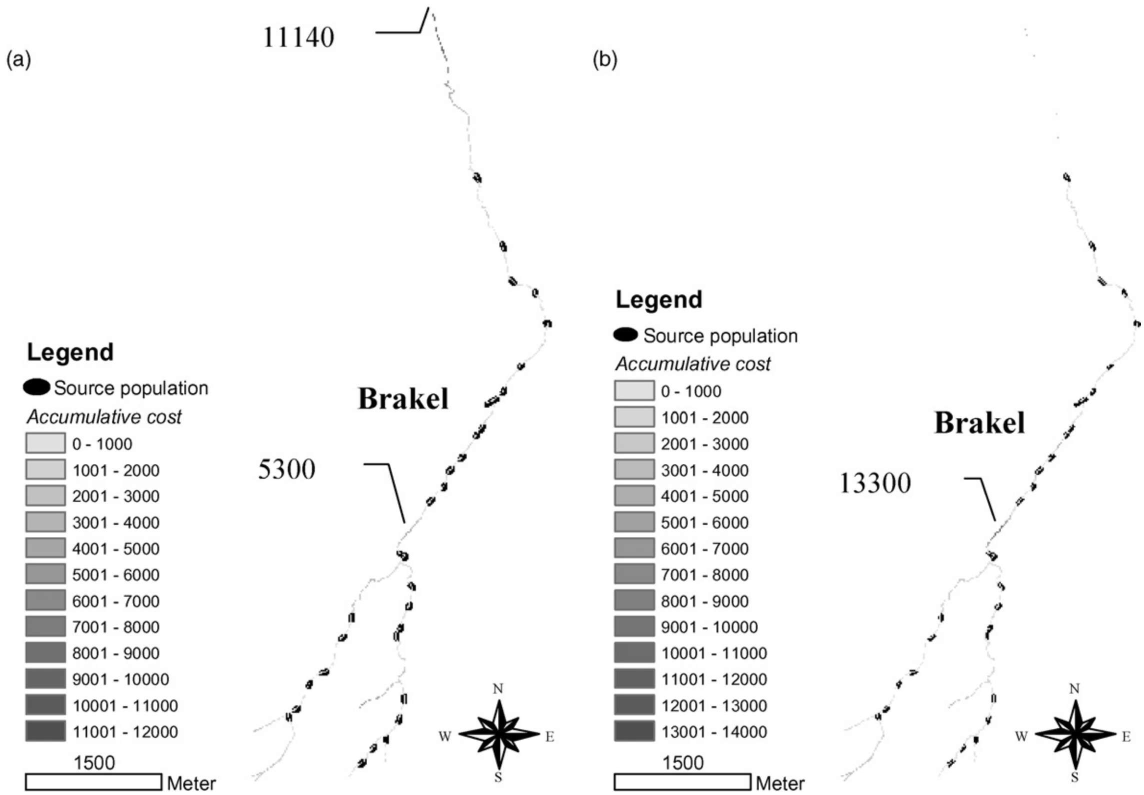


Fig. 6 – Map of the accumulative cost for migration downstream (a) and upstream (b) through the river from the source population of *Baetis*. The highest accumulative cost(s) are indicated.

stream point of the study area (Fig. 5). At the centre of Fig. 5, the influence of Brakel city on the accumulative cost value could be observed.

The highest accumulative cost for downstream migration (11,140 units) was located at the most downstream point (Fig. 6a). The culverted river section near Brakel city obtained also a high cost (5300 units). The maximum accumulative cost for upstream migration (13,300 units) was reached at this culverted river section (Fig. 6b).

3.3. *Migration model for Ephemera (Ephemeroptera)*

For migration through the air, a maximum accumulative cost of almost 36,000 units was obtained. To reach the most downstream part of the Zwalm river, a cost of 17,700 units has to be conquered by *Ephemera*. In Fig. 7, the influence of Brakel city on the migration cost can easily be detected. There is a high increase in cost to migrate from one of the source populations to a point situated in Brakel city. As mentioned before, migration through the river was of minor importance for *Ephemera*.

3.4. *Migration model for Limnephilidae (Trichoptera)*

For Limnephilidae, higher accumulative cost values for migration through the air were obtained in comparison with *Baetis* and *Ephemera* because a higher resistance value was attributed to points outside a strip of 20 m around the river. In this way, the maximum accumulative cost for migration through the air was about 230,000 units. This value was about 10 times higher than the maximum accumulative cost for *Baetis* and *Ephemera*. When only points in the vicinity of the river were taken into account, the highest accumulative cost of 39,500 units was detected for the most downstream point of the Zwalm river (Fig. 8). This is still two times higher than for *Ephemera* which has a similar source population pattern.

Because the resistance values for upstream and downstream migration were equal (except for the weir) (cf. Table 4), the same map could be used for both accumulative costs. The maximum accumulative cost (85,000 units) was obtained for the most downstream point of the Zwalm river (Fig. 9). Also the strong increase of the accumulative cost to migrate through the culverted river section could be observed. However, both accumulative costs could only be applied for the downstream migration because downstream of these points no source populations of Limnephilidae were found. In this way, upstream migration is out of the question at these points. For upstream migration, the highest accumulative cost (2100 units) was reached in a tributary of the brook Dorenbosbeek (Fig. 9).

3.5. *Model simulation of a river restoration scenario: removal of a weir*

In this part, the effect of the removal of the weir in the studied river section on *Baetis*, *Ephemera* and Limnephilidae has been simulated. The weir for water quantity control near the mill Boembekemolen is situated in the downstream part of the selected section of the Zwalm river basin. The weir obstructs

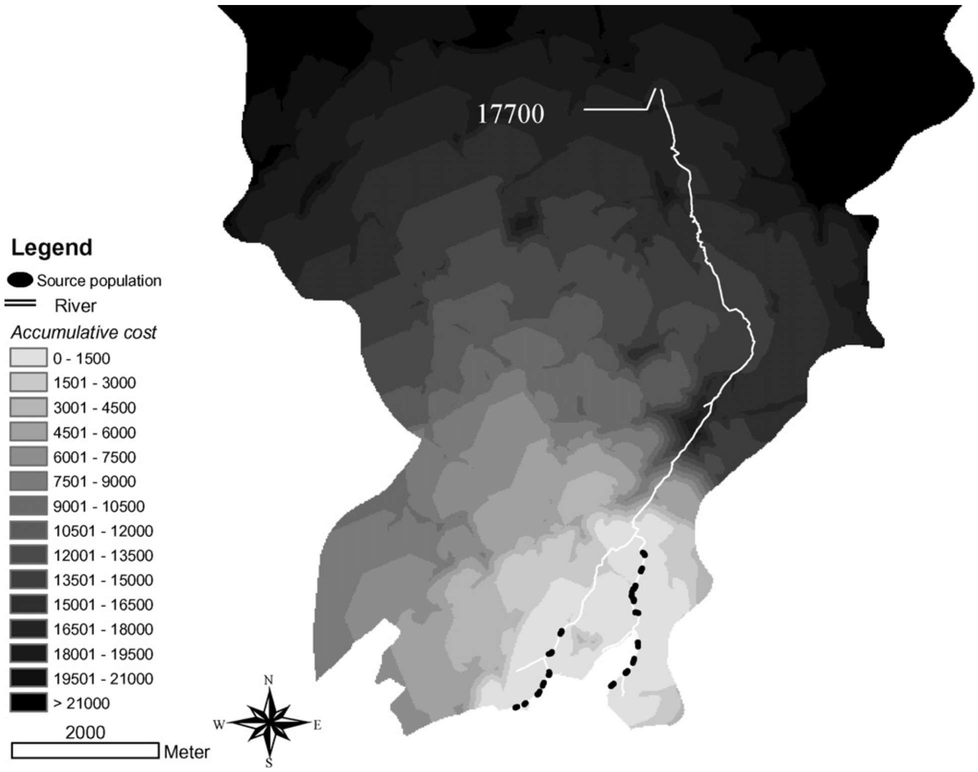


Fig. 7 – Map of the accumulative cost for migration through the air from the source populations of *Ephemera*. The highest accumulative cost to reach a point along the river is indicated.

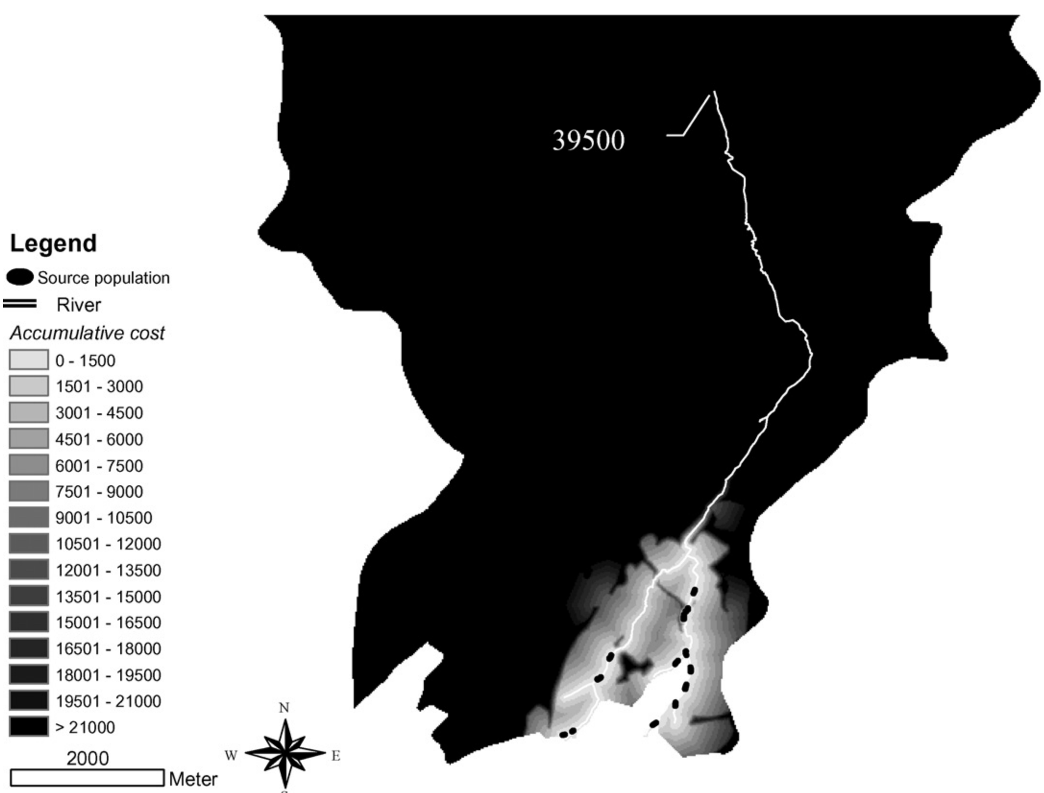


Fig. 8 – Map of the accumulative cost for migration through the air from the source populations of Limnephilidae. The highest accumulative cost to reach a point along the river is indicated.

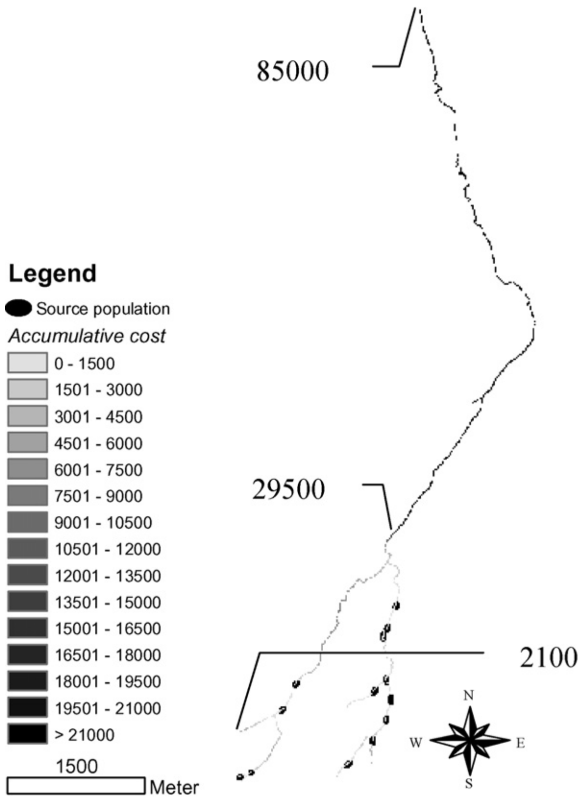


Fig. 9 – Map of the accumulative cost for migration downstream and upstream through the river from the source populations of Limnephilidae. The highest accumulative costs are indicated.

the migration of fish and other aquatic organisms, including macroinvertebrates. In addition, up and downstream of the weir, the Zwalm river is characterized by a modification of the flow channel. Upstream of the weir, the river is drastically deepened. Just in front, the depth can be nearly around two meters depending on the control level of the weir and the amount of sediments accumulated at the site. During the measurements, an average depth of more than one meter was recorded, what is much deeper than under natural conditions. Also the flow velocity is reduced drastically, creating an almost stagnant water body immediately upstream of the weir (Belconsulting, 2003). This situation results in direct and indirect impacts on the river biology. A direct impact is that the shear stress is quite different, being an advantage for *Asellus* (Crustacea, Isopoda) for instance, but for some insect larvae like *Baetis* which can profit from a continuous water flow over their gills on the back of their body, these artificially induced conditions are less optimal. The indirect effects of the decreased flows can play a crucial role for the river biology as well. As a result of the reduced flows, there is a serious accumulation of sediments (due to the erosion problems in the area), containing organic materials and probably also toxic materials, such as pesticides from runoff of agricultural soils. The organic compounds are degraded by the local microbiota, reducing the amount of dissolved oxygen in the water in particular near the bottom of the deepened system. The oxygen increase is not taken into account in case of weir removal in the presented simulations, because it is very difficult to predict this value on the basis of expert knowledge without a water quality model.

Removing the weir has an impact on several structural components of the river as well. In the upstream section of the removed weir, flow velocity will increase while width and depth will decrease. Also the quality of the channel morphology will evolve positively because of an increased meandering of the river, the development of pools and riffles, and the creation of natural hollow banks. These changes are taken into account when predicting the effect of weir removal on the habitat suitability for *Baetis*, *Ephemera* and Limnephilidae. In combination with expert knowledge, the expected values of the altered stream characteristics were obtained on the basis of monitored conditions about 1 km upstream of the weir, where the weir effect is about nihil. In this way, the input variables for the validation dataset of the ANN models reflecting these changed characteristics were altered over a distance of about 200 m downstream (two sites) and 1 km (five sites) upstream of the removed weir.

The ANN models were used to predict the habitat suitability for *Baetis*, *Ephemera* and Limnephilidae. Good CCI percentages of 73.6 ± 3.8, 95.2 ± 3.8 and $88.3 \pm 0.0\%$ for, respectively, *Baetis*, *Ephemera* and Limnephilidae were obtained in the test set based on the three-fold cross-validation procedure. Derived from the standard deviation, the CCIs seemed to remain rather constant. The Cohen's kappa values on the other hand were 0.20 ± 0.18, 0.77 ± 0.16 and 0.04 ± 0.08 for, respectively, *Baetis*, *Ephemera* and Limnephilidae. The threshold value of 0.4 for Cohen's kappa was only met for the *Ephemera* model, in spite of the low prevalence of 11.3%, but not for the *Baetis* and Limnephilidae models.

In Table 6, the outcomes of the ANN models are presented. In brackets, the number of folds supporting the presence/absence label is indicated. Before weir removal, *Baetis*, *Ephemera* and Limnephilidae were not found at all sites. For the three taxa, the ANN models were able to classify the actual conditions (=the conditions before weir removal) well, based on the environmental variables. The taxa were predicted as being absent at all sites. Despite the altered conditions after weir removal, no shifts in habitat suitability were predicted for *Baetis*, *Ephemera* and Limnephilidae. All restored sites were still predicted as unsuitable, most probably as a result of wastewater discharges in some of the upstream river parts.

Although the restored river section was evaluated as unsuitable for *Baetis*, *Ephemera* and Limnephilidae, the developed migration models still could be applied to calculate the migration possibilities from the source populations to the restored parts. This could help the river managers to make a decision on whether or not additional restoration works are necessary. For instance, if also the water quality was improved (e.g. by the installation of local small scale wastewater treatment plants), it would be likely that *Baetis* would recolonize the restored upstream river section since several source populations were already observed over there. For this reason, the migration model developed in Section 3.2 was applied to simulate the recolonization possibility of *Baetis* in the restored site. Some of the altered stream characteristics after weir removal would have an effect on the migration model of *Baetis* (e.g. fraction of boulders and flow velocity). In addition, an impor-

Table 6 – Observed and predicted taxon presence/absence values of the actual and altered conditions (in brackets the amount of folds out of a total of three that support the outcome) according to the 24-10-1 ANN models

Site (distance from weir)	Observed	Predicted (under actual conditions)	Predicted (under altered conditions)
Baetis			
1 (±210 m downstream)	Absent	Absent	Absent (3/3)
2 (±20 m downstream)	Absent	Absent	Absent (3/3)
3 (±30 m upstream)	Absent	Absent	Absent (3/3)
4 (±280 m upstream)	Absent	Absent	Absent (3/3)
5 (±550 m upstream)	Absent	Absent	Absent (3/3)
6 (±870 m upstream)	Absent	Absent	Absent (3/3)
7 (±1130 m upstream)	Absent	Absent	Absent (3/3)
Ephemera			
1 (±210 m downstream)	Absent	Absent	Absent (3/3)
2 (±20 m downstream)	Absent	Absent	Absent (3/3)
3 (±30 m upstream)	Absent	Absent	Absent (3/3)
4 (±280 m upstream)	Absent	Absent	Absent (3/3)
5 (±550 m upstream)	Absent	Absent	Absent (3/3)
6 (±870 m upstream)	Absent	Absent	Absent (3/3)
7 (±1130 m upstream)	Absent	Absent	Absent (3/3)
Limnephilidae			
1 (±210 m downstream)	Absent	Absent	Absent (3/3)
2 (±20 m downstream)	Absent	Absent	Absent (3/3)
3 (±30 m upstream)	Absent	Absent	Absent (3/3)
4 (±280 m upstream)	Absent	Absent	Absent (3/3)
5 (±550 m upstream)	Absent	Absent	Absent (3/3)
6 (±870 m upstream)	Absent	Absent	Absent (3/3)
7 (±1130 m upstream)	Absent	Absent	Absent (3/3)

'Under actual conditions' and 'under altered conditions', respectively, means before and after weir removal.

tant migration barrier would disappear. Taking these changes into account for *Baetis*, the accumulative cost for migration downstream through the river to site 3 (Table 6) would drop significantly as presented in Fig. 10a (5900 units) compared to Fig. 6a (±11,100 units). To get insight in the duration of the possible recolonization through the river, the distances, which were calculated to obtain the resistances, were used. Therefore, active and passive migration were taken into account. For each segment, the time to migrate through that segment was calculated. This was based on the maximum distance which could be covered through that segment in 1 day. Finally, the sum from the source population to the restored river section was considered to estimate the total recolonization time. The total distance between both points is 1942 m. After weir removal and restoration of the river habitat, this would result in a total migration time for *Baetis* of approximately 2 years. On the other hand, weir removal would only have a minor effect on the accumulative cost for migration through the air as shown in Fig. 10b (2140 units instead of ±2400 units). The time to recolonize the restored river section through the air would be about 275 days. In this way, one could conclude that the shortest path with the least accumulative cost from the 'cheapest' source population to site 3 would be through the air (Fig. 10b).

4. Discussion

To model the migration and recolonization possibilities of *Baetis*, *Ephemera* and Limnephilidae in the Zwalm river basin the Cost Weighted Distance function was applied. This cost–distance function is an interesting and widespread tool to model movement behaviour in ecology and is proven to perform better than the Euclidean distance function (e.g. Ferreras, 2001; Chardon et al., 2003; Verbeylen et al., 2003). The latter function is commonly used in spatial population studies to model migration and connectivity between habitats but it is only a simple measure for the shortest distance between a suitable habitat, called a 'patch' in spatial ecology, and its nearest neighbour (Moilanen and Hanski, 2001). The role of the environment on the connectivity of suitable habitat and the species-specific migration behaviour through the environment is thereby ignored (Tischendorf and Fahrig, 2000). However, the importance of the environment for migration is increasingly being acknowledged. The importance of this topic has been illustrated in detail for terrestrial ecosystems (mammals: e.g. Bowne et al., 1999; Ferreras, 2001; birds: e.g. Brooker et al., 1999; butterflies: e.g. Haddad, 1999; Conradt et al., 2001). Recently, its usefulness and suitability is also demonstrated for aquatic ecosystems (Michels et al., 2001).

Some aspects of the method have to be emphasized before using the Cost Weighted Distance function. In the first place, the quality of the maps is highly important (Adriaensen et al., 2003). All GIS packages use grid maps as input for the least-cost model. This implies that a lot of GIS information available in vector format (e.g. digitalized watercourses, land use, . . .) has to be converted to grids before the model can be applied. Since the grid map is the only input, its quality is decisive for the quality and reliability of the resulting cost map. This has important consequences for a few aspects of

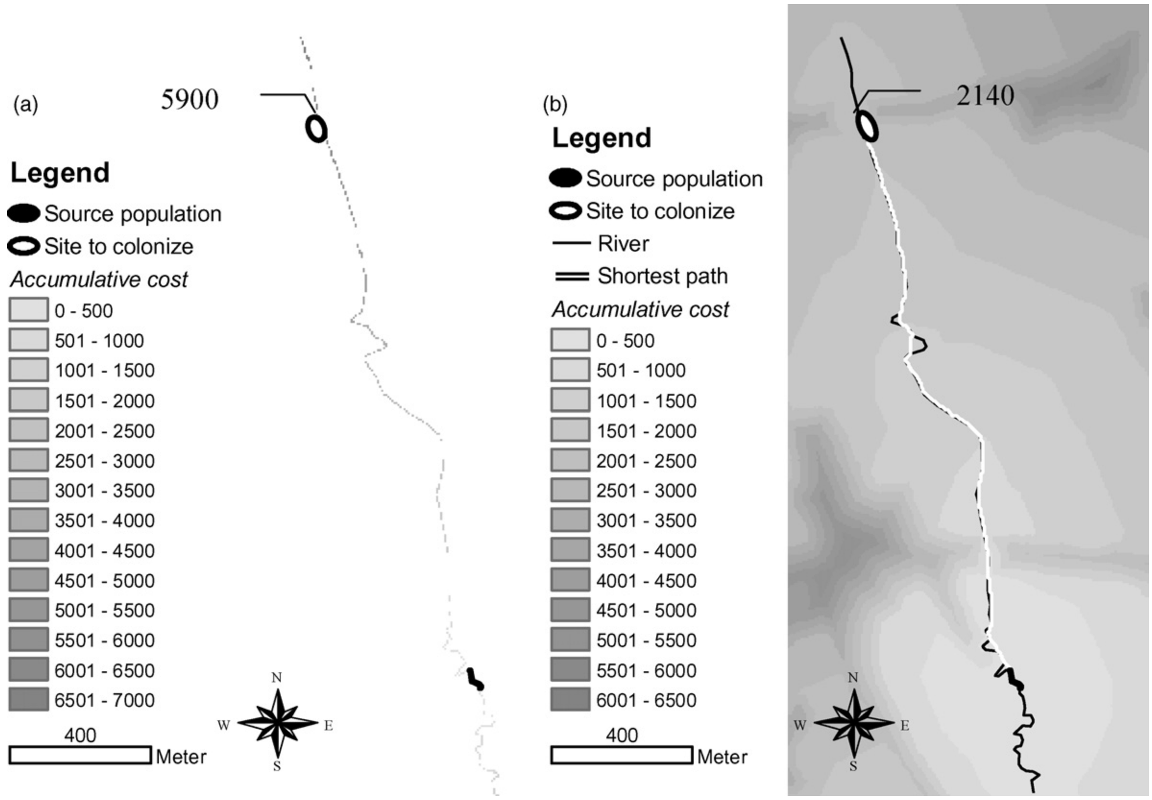


Fig. 10 – Map of the accumulative cost for migration downstream through the river (a) and through the air (b) from the source populations of *Baetis*. The accumulative costs to reach site 3 (Table 6) are indicated. The shortest path from the 'cheapest' source population to site 3 is shown.

the map. Relatively low resolution (large grid cells) may be used for general land cover since parcels mostly have larger dimensions. However, resolution is crucial for smaller or narrower elements in the landscape (e.g. watercourses). In this study, the optimum size chosen for one grid cell was 5 pixels. In this way, the grid size was small enough to capture the required detail, but large enough so that computer storage and analysis could be performed efficiently. Secondly, the setting of resistance values in the resistance layer is biologically probably the most important step in the process of calculating the cost for migration (Adriaensen et al., 2003). It is the link between the (non-ecological) GIS information and the ecological–behavioural aspects of the mobility of the organisms. Especially, when the purpose is to construct a predictive model for conservation or restoration management, it is critical that the model (and thus resistance and connectivity measures) is rigorously parameterized using empirical data and validated in independent landscapes (see Moilanen and Hanski, 2001; Schadt et al., 2002). For most organisms however, setting the resistance values will be a difficult process in which expert judgement and data available in literature will play an important role (see e.g. Schadt et al., 2002). Also in this study, resistance values for *Baetis*, *Ephemera* and Limnephilidae were mainly based on expert and literature knowledge. Only for the estimation of the resistance for passive downstream migration (=drift) of *Baetis*, actual field data of flow velocity could be used based on Elliott (2002). Although the resistance values for migration through the air/over land were very similar for *Baetis*, *Ephemera* and Limnephilidae (Table 3), the resulting maps of the accumulative costs were quite different. The main reason is the location of the source populations. Source populations of *Baetis* are spread over the whole study area while *Ephemera* and Limnephilidae were only found in the brooks Verrebeek and Dorenbosbeek (Table 5). The main difference between the accumulative cost maps of *Ephemera* and Limnephilidae was attributed to the limited dispersal of Limnephilidae in a strip of 20 m around the watercourse. In this way, the highest cost for migration through the air was a few orders lower for *Baetis* than for *Ephemera* and Limnephilidae. Similar conclusions could be drawn for migration through the river.

To get insight in the reference conditions as is necessary for the implementation of the European Water Framework Directive (EU, 2000), the removal of the weir for flood control near the mill Boembekemolen can be seen as an interesting virtual restoration action to be undertaken. By knowing what would be the ecological shifts, one is able to get insight in the reference communities, but also whether it is really worth to consider such a drastic restoration effort towards a near natural condition and increasing the risks for flooding downstream during intensive rain events as a potential consequence. Most probably, this situation with a weir for flood control cannot be altered drastically, and the attribution of this site as a strongly modified water body will probably be necessary and be defended from a social–economical perspective wider than nature conservation. To model the effects

of weir removal on *Baetis*, *Ephemera* and Limnephilidae in the Zwalm river, ANN models were applied to simulate the habitat suitability after river restoration. Ecosystem models such as ANNs are useful tools to support decision-making in river management (Goethals and De Pauw, 2001). These models allow for a better interpretation of the river status, detection of the causes of the status of a river, and optimization of the assessment methods. They can help to find the major gaps in our knowledge of river systems and help to set up cost-effective monitoring programmes. Last but not least, these ecological models can allow for calculating the effect of future river restoration actions on aquatic ecosystems and supporting the selection of the most sustainable options. In particular, models that can predict the habitat requirements of organisms are of considerable importance to ensure that the planned restoration actions have the desired effects on the aquatic ecosystems. In general, ANN models are recognized to make reliable predictions of river invertebrates (e.g. Walley and Fontama, 1998; Schleiter et al., 1999; Wagner et al., 2000; Hoang et al., 2001; Park et al., 2001). In the present study however, by using a three-fold cross-validation procedure, the predictive results were not satisfying. Although good predictions were obtained for the presence/absence of *Baetis*, *Ephemera* and Limnephilidae based on the CCI (CCI > 70%), the Cohen's kappas indicated that, except for *Ephemera*, this high CCI was for a major part related to the relatively low prevalence of the three taxa in the dataset (*Baetis*, *Ephemera* and Limnephilidae were present in, respectively, 26.0, 11.3 and 11.3% of the sites), and the related ease to make good predictions, even without the extraction of information from the environmental variables (Dedecker et al., 2004). This directly illustrates the convenience of using two performance measures when predicting presence/absence data.

Despite the altered conditions after weir removal, no shifts in habitat suitability were predicted for *Baetis*, *Ephemera* and Limnephilidae. Although the model performance was not that high based on the test dataset, the unaltered conditions of the physical and chemical variables after weir removal were probably the reason why the habitat suitability was still predicted as unacceptable for these indicators of good water quality. The increased structural quality of the river was apparently insufficient to restore the habitat for these sensitive taxa. The high importance of water quality variables such as dissolved oxygen, conductivity, total phosphorus, nitrate, ... to describe the habitat suitability of these taxa was confirmed when sensitivity analyses were performed on the dataset. Therefore, to include the changes in water quality after weir removal, it would be useful to link the developed habitat suitability model to a river water quality model (e.g. QUAL2E; Brown and Barnwell, 1987). A case study on *Gammarus pulex*, a riverine crustacean amphipod, however illustrated that the removal of the weir resulted in an improvement of the habitat suitability. The ANN model predicted that after restoration the habitat was suitable again for *Gammarus pulex*. Besides, the migration model indicated that the restored parts of the river would be recolonized within about 2 months (Dedecker et al., 2006). On the other hand, according to the habitat suitability models, the restored river section was not suitable for *Baetis*, *Ephemera* or Limnephilidae. However, if also water quality was improved, for instance by a reduction of the diffuse pollution origination from agricultural activities and by a more consistent connection of households to the sewerage system via local small scale wastewater treatment systems, it would be likely that *Baetis* would recolonize the restored river section because upstream, several source populations were observed. After weir removal and restoration of the river habitat, this would result for *Baetis* in a total migration time through the air and the water of, respectively, 275 days and 2 years. Assuming that the restored habitat was suitability for Limnephilidae and *Ephemera* as well, it is less likely that they would recolonize these river sections since source populations were only observed in the headwaters (the brooks Verrebeek and Dorenbosbeek) of the Zwalm river basin, which are more than 7 km upstream of the restored river. The migration models indicated that it would take almost 6 years to migrate downstream through the river (assuming that also the habitat suitability of the watercourses between source population and restored river section improve), while migration time through the air would be approximately 3 years.

The developed migration models using the cost–distance function has a whole range of applications. Not only the migration possibilities of observed macroinvertebrates within the study area could be modelled but also by extension of other species including nearly extinct as well as invasive exotic species could be of major importance in river restoration management. With migration models, also the effects of certain interventions (e.g. weir removal or remeandering projects) in view of river management planning can be evaluated in a more reliable and integrated way compared to the local habitat suitability models. Similar strategies also need to be developed for fish, seen the importance of migrating species in the assessment based on the Index of Biotic Integrity (IBI) for upstream brooks in Flanders (Breine et al., 2004). In addition, the scale of the developed models will have to be extended to the whole Zwalm river basin. Extension of the intensive monitoring campaign as done for the selected part of the Zwalm river basin, would however be very costly and time consuming. Therefore, using aerial photographs and remote sensing techniques in combination with digital maps to extract the necessary information would be recommendable. Finally, it has been shown that the combined use of migration and habitat suitability models could allow river managers to make a more rational selection among different restoration scenarios. In this way, they can find out in advance whether and when a restoration option will have a desired effect or not.

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